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by

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DIAGNOSIS OF FRONTOGENESIS OF MEIYU FRONT

Yi Bing Qiao Quanming Zhang Li /92*

ABSTRACT

This article analyzes the frontogenesis processes associated with one instance of Meiyu front. In conjunction with this, use is made of frontogenesis functions and temperature balance equations. Discussions are made of factors influencing Meiyu front formation and maintenance. Results clearly show that sensible heating is the main factor causing the Yangtze-Huai river valley lower layer frontal area to disappear and latent heating as well as deformations associated with horizontal motion are the main factors associated with maintaining the existence of Meiyu fronts.

KEY WORDS: Meiyu front, Frontogenesis, Diagnosis

I. INTRODUCTION

Meiyu is the main weather phenomenon appearing in early summer in the Yangtze River valley and the area of Japan. Early Meiyu research began with monsoons [1]. Later, from the concepts of air masses and fronts, discussions were made of the formation and maintenance of Meiyu fronts as well as their changes [2,3] and relationships between Meiyu and changes in atmospheric circulation. Beginning in the 1970's, with regard to conditions producing Meiyu rainstorms as well as physical processes [5,6] and Meiyu front structure [7,9] also received some study. It was recognized that, during Meiyu periods, lower layer frontal zone structures gradually disappear. Kato did research on abrupt changes associated with Meiyu front structures on the Chinese mainland from May - June 1979 [10]. In conjunction with this, it was pointed out that North China plain sensible heating is the reason for the sudden disappearance of Yangtze-Huai region lower layer frontal zones. However, with regard to the effects of

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* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

other factors in Meiyu front formation processes as well as the maintenance of medium and high layer frontal zones, there was not much discussion.

This article carries out diagnostic analyses of the structure of one Meiyu front from 22-30 June 1981 as well as its frontogenesis processes. Use is made of frontogenesis functions and heat balance equations to discuss factors influencing Meiyu front formation and maintenance.

II. DATA AND ANALYSIS METHODS

This article goes through objective analysis of key conventional meteorological factors associated with ground surfaces and standard isobaric surfaces at 0800 and 2000 from 22-30 June 1981. It arrives at key values associated with points on a 2.5°x2.5° grid within the 20-47.5°N and 90-127.5°E range.

The frontogenesis function F in coordinate system P is:

$$F = \frac{d}{dt}|\nabla\theta| = F_H + F_V + F_\infty, \tag{1}$$

In this,

$$F_H = \frac{1}{C_p|\nabla\theta|}\left(\frac{p}{1000}\right)^{R/Cp}(\nabla\theta \cdot \nabla H), \tag{2}$$

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$$F_V = -\frac{1}{|\nabla\theta|}\left\{\frac{1}{2}\left[\left(\frac{\partial\theta}{\partial x}\right)^2 - \left(\frac{\partial\theta}{\partial y}\right)^2\right]\left(\frac{\partial v}{\partial x} - \frac{\partial v}{\partial y}\right) + \frac{\partial\theta}{\partial x}\frac{\partial\theta}{\partial y}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right\}$$
$$- \frac{1}{2|\nabla\theta|}|\nabla\theta|^2\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \tag{3}$$

$$F_\infty = -\frac{1}{|\nabla\theta|}\frac{\partial\theta}{\partial p}\left(\frac{\partial\theta}{\partial x}\frac{\partial\omega}{\omega x} + \frac{\partial\theta}{\partial y}\frac{\partial\omega}{\partial y}\right), \tag{4}$$

H is the nonadiabatic heating rate, including sensible heating, large scale latent heat of condensation, and latent heat of convective condensation.

Visual heat sources and visible water vapor collection are respectively

$$Q_1 = C_p \left[\frac{\partial \overline{T}}{\partial t} + \overline{\mathbf{V}} \cdot \nabla \overline{T} + \left(\frac{p}{1000} \right)^{R/C_p} \omega \frac{\partial \theta}{\partial p} \right] \tag{5}$$

$$= \overline{Q}_R + L(\overline{C} - \overline{e}) - \frac{\partial}{\partial p} (C_p \overline{\omega' T'}), \tag{6}$$

$$Q_2 = -L \left(\frac{\partial \overline{q}}{\partial t} + \nabla \cdot \overline{q}\, \overline{\mathbf{V}} + \frac{\partial}{\partial p} \overline{\omega}\, \overline{q} \right) \tag{7}$$

$$= L(\overline{C} - \overline{e}) + L \frac{\partial}{\partial p} (\overline{\omega' q'}), \tag{8}$$

In this, Q_R, C, and e are, respectively, radiation heating rate, condensation rate, and evaporation rate $\overline{Q}_R$ values picking June climatic values [11]. From equations (6) and (8), one has

$$Q_1 = Q_2 + \overline{Q}_R + g\partial Fc / \partial p. \tag{9}$$

Because of this, temperature equilibrium equations are

$$\underbrace{\frac{\partial \overline{T}}{\partial t}}_{A} = \underbrace{\frac{1}{Cp} (Q_2 + \overline{Q}_R)}_{B} + \underbrace{\frac{g}{Cp} \frac{\partial Fc}{\partial p}}_{C} \underbrace{- \overline{\mathbf{V}} \cdot \nabla \overline{T}}_{D} \underbrace{- \left(\frac{p}{1000} \right)^{R/C_p} \overline{\omega} \frac{\partial \overline{\theta}}{\partial p}}_{E} \tag{10}$$

In this, as far as $\frac{g}{C_p} \frac{\partial}{\partial_p} Fc$ are concerned, complementary terms are given. Finally, calculation results are taken and averaging carried out in different zones. Within the 110°-120°E range, we took 30°-35°N to represent the Meiyu zone of clouds and rain (central area), 37.5°-42.5°N to represent the temperate zone system area (northern area), and 22.5°-27.5°N to represent the southwest monsoon control area (southern zone).

III. MEIYU FRONT DEVELOPMENT

On June 22, 1981, the Yangtze-Huai area entered into the Meiyu period. From the 24th - 27th, the Yangtze-Huai area saw the appearance of Meiyu rainstorms. On July 3d, the Meiyu finished. From now on, in this article, the phase (22-23) associated with the entry of Meiyu into the Yangtze-Huai area and the beginning appearance of rainstorms is called the initial Meiyu period, and the 24th-27th is called the Meiyu rainstorm period.

At 2000 on the 19th, there was cold air splitting off south. As far as the ground surface is concerned, in the North China-Northwest area, there was a cold front moving toward the southeast. With regard to the development processes associated with front strengths, it is possible to use Fig.1 to explain. At 500hPa and 300hPa, after the entry of the Meiyu, temperature gradients enlarged. Relatively strong frontal zones in upper layers of the troposphere were maintained right through to the conclusion of the Yangtze-Huai area rainstorms. However, at 850hPa, after entry of the Meiyu, frontal zone strengths diminished. After entering the rainstorm period, the strengths diminished a step further, even to the point of there appearing a situation associated with temperature gradient reversal.

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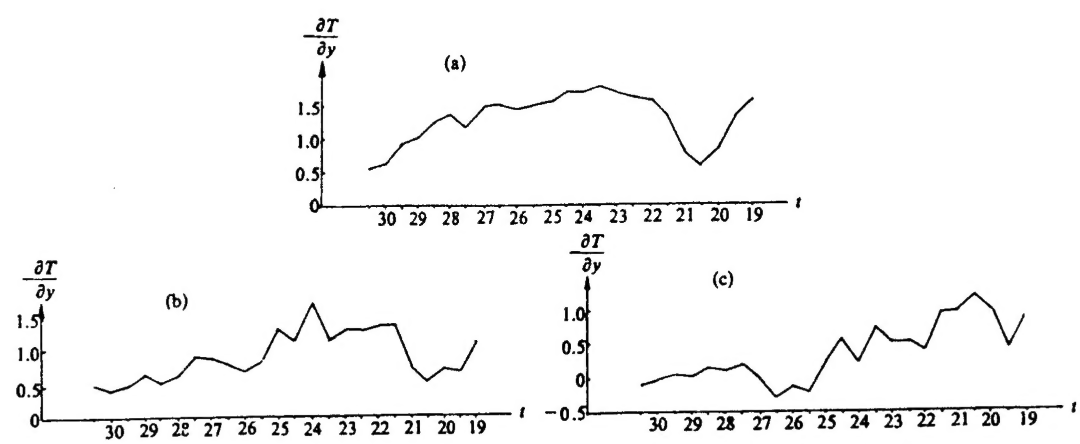

Fig.1 Time Development of Average Northward Temperature Gradients from 110-120°E Longitude in the Vicinity of Shear Lines in June 1981 (Degrees/100km) (a) 300hPa (b) 500hPa (c) 850hPa

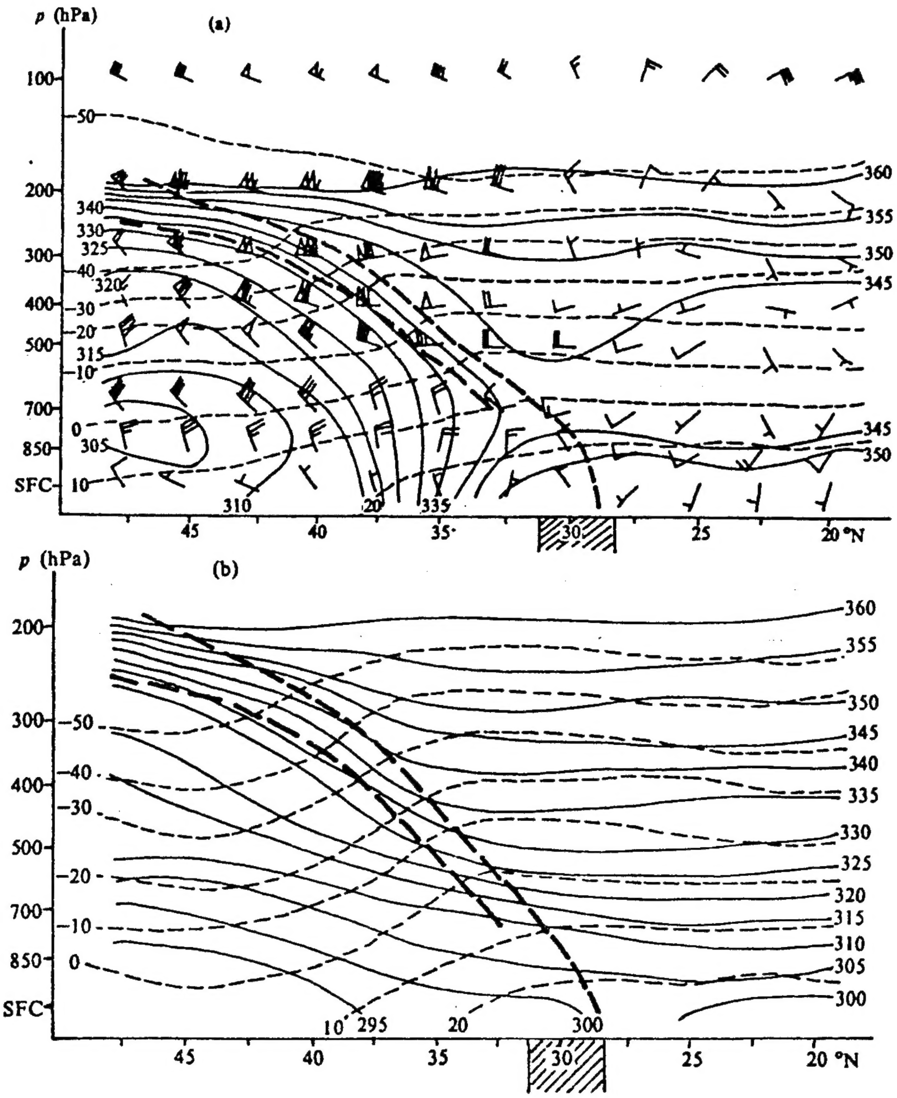

Fig.2 Average Latitudinal Vertical Cross Section 110-120°E at 0800 on 22 June 1981
Key: (a) Temperature (T) and Hypothetical Corresponding Position Temperatures (O_{se}) (b) Dew Point Temperatures (T_d) and Position Temperatures (O) Among these, the double thick broken lines represent frontal areas. Single thick broken lines represent cyclone type shear lines. Thin solid lines are θ or θ_{se} lines (°C). The lower shaded area represents the appearance range for thunderstorms or precipitation.

As far as the early Meiyu period is concerned (Fig.2), 700-200hPa, there existed a clear frontal area slanting toward the north following altitudes. Within the frontal area, temperature gradients and position temperature gradients were both relatively large. Moreover, θ lines and θ_{se} lines are close to parallel with frontal areas. At 700-300hPa on the two sides of the front, wind shear and dew point correlations are relatively obvious. At 850hPa and ground surface, wind shears are also very clear. However, temperature gradients in the vicinity of shear lines as well as dew point temperature gradients are both not large. Fronts in low layers are already indistinct.

With regard to the Meiyu rainstorm period (Fig.3), at 500-300hPa on the north side of Meiyu rain and cloud belts, there still exist relatively clear frontal zones. Within frontal areas, temperature gradients and dew point temperature gradients are both very large. θ and θ_{se} gradients are also relatively large. Wind shears on the two sides of fronts are also very clear. However, θ lines are no longer parallel to frontal zones. θ_{se} lines--at 300hPa and below--are almost vertical, showing clearly that convection activity is very strong. In low layers below 700hPa, in the vicinity of Meiyu rain and cloud belts, there still exists a shear line. Dew point temperature gradients in the vicinity of shear lines and θ_{se} gradients are relatively large. However, wind shears in layers close to the ground have already turned into warm type shears. Temperature advection is warm advection. Traces of cold fronts have already completely disappeared. Moreover, temperature gradients in the vicinity of low layer shear lines as well as position temperature gradients are very small. Sometimes, temperatures on the north side of shear lines are higher than on the south side. Because of this, during Meiyu rainstorm periods, troposphere low layers often do not harbor large scale frontal areas in the classic sense. They only hold a wind shear line.

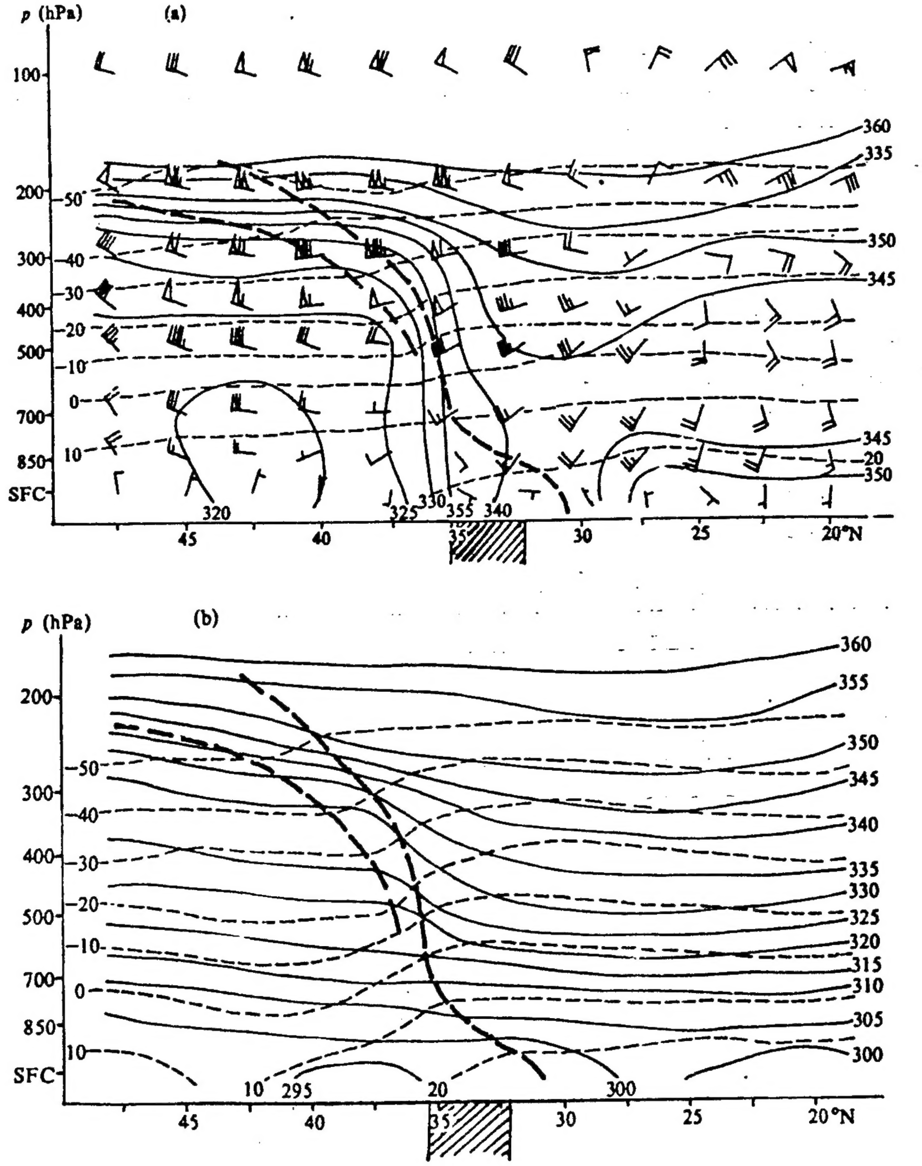

Fig.3 Average Latitudinal Direction Vertical Cross Section 110-120°E at 0800 on 24 June 1981. The Rest Is the Same as Fig.2.

IV. RELATIONSHIP BETWEEN SENSIBLE HEATING AND LOW LAYER FRONT DISAPPEARANCE

We calculated Meiyu initial period and rainstorm period low layer temperature balances, using them in order to explain transformations in low layer front structures.

Table 1 is calculation results associated with various terms in equation (10) (in them, the north zone is taken as the North China area associated with the existence of low layer warm ridges being 110-120°E, 40-50°N). In Meiyu initial periods and rainstorm periods, North China area low layers all have relatively large rates of temperature increase. In Meiyu initial

TABLE 1 JUNE 1981 850hPa AIR TEMPERATURE CHANGES AND BALANCE (Unit: °C/d)

(1) 日期 / (2) 项目 / (3) 区域	22日 (4) A	B	C	D	E	24日 (4) A	B	C	D	E
(5) 北 区	4.02	−0.77	−4.02	2.16	6.65	1.37	−2.65	5.62	−0.50	−1.10
(6) 中 区	−1.86	10.01	−10.81	−0.43	−0.63	0.56	−3.72	2.38	1.40	0.50
(7) 南 区	−1.46	0.56	2.40	−0.20	−4.22	0.24	−0.57	3.31	−1.20	−1.30

Key: (1) Date (2) Item (3) Area (4) Day (5) North Zone (6) Middle Zone (7) Southern Zone

phases, the primary factor creating North China area temperature rises are the actions of down sinking movements (term E) and warm advection (term D). Further analysis clearly shows that North China area warm advection is a cumulative result associated with west side sensible heating. In order to verify this conclusion, we calculated temperature balance for the northwest area (102.5-107.5 °E, 40-45 °N), and took temperature advection terms dividing them into the two terms $D_x = -u\partial T/\partial x$ and $D_y = -v\partial T/\partial y$ (Table 2). It is possible to see, during Meiyu initial periods, strong northwest area vertical vortical flux convergence (as far as term C is concerned, at 850hPa, the prime contributor is sensible heating from the ground surface). Besides counteracting cold advection coming from the north as well as the temperature lowering effects of term B, residual amounts heat the low layer atmosphere, causing air moving east--when it arrives in the North China area--to turn into strong warm advection coming from the west. It is adequate to offset cold advection coming from the north.

TABLE 2 JUNE 1981 850hPa AIR TEMPERATURE CHANGES AND BALANCE (Unit: °C/d)

(1) 日期 / (2) 项目 / (3) 区域	22日 (4)						24日 (4)					
	A	B	C	D_x	D_y	E	A	B	C	D_x	D_y	E
(5) 北 区	4.02	−0.77	−4.02	4.31	−2.15	6.65	1.37	−2.65	5.62	0.20	−0.70	−1.10
(6) 西北区	4.01	−3.12	8.34	0.80	−1.03	−0.98	2.21	0.06	1.05	0.70	−0.35	−0.75

Key: (1) Date (2) Item (3) Area (4) Day (5) North Zone (6) Northwestern Zone

Moreover, in the Meiyu area of cloud and rain (central zone), the initial Meiyu period is vortical flux convergence temperature rises and evaporation temperature decreases associated with falling rain drops, coming close to balance and making air temperature changes very small.

In areas south of Meiyu cloud and rain belts (southern zone), sensible heating is primarily offset by adiabatic rises and cooling, making air temperature changes relatively small.

In this, during initial Meiyu periods, northern zone rates of temperature increase are the largest. Central zone rates of temperature drop are the strongest. Thus, in low layers, it is possible to make the North China zone show the gradual appearance of warm ridges in close to an east west direction and make the bottom of Meiyu cloud and rain belts correspond to a cold trough. In Meiyu rainstorm periods, northern zones still have relatively large rates of temperature increase. Rates of temperature increase associated with central zones and southern zones are very small. As a result, this type of distribution characteristic associated with low layer temperature fields is still capable of support. The existence of large scale low layer frontal areas is destroyed. Therefore, the disappearance of low layer fronts in Meiyu periods can be explained using sensible heating. /97

V. FRONTOGENESIS FACTORS INFLUENCING MEIYU FRONTS

As far as factors influencing frontogenesis are concerned, there are various types of nonadiabatic processes, deformations as well as convergence (divergences) given rise to by horizontal motions, and horizontal distributions of vertical motions. With regard to frontogenesis functions given rise to in order to do quantitative calculations of these factors, it is possible to understand what sorts of actions they have in the formation and maintenance of Meiyu fronts. Table 3 is the average frontogenesis situation for Meiyu periods.

In initial Meiyu periods, northern zone 850-700hPa troposphere low layers have weak frontal dissipation. 500-200hPa middle and high layers have relatively strong frontogenesis. Moreover, horizontal motion terms, nonadiabatic terms, and torsion terms play roles together. Also, in central zones, 850-700hPa troposphere low layers have relatively strong frontal dissipation. Nonadiabatic terms play the key role. As a result, during initial Meiyu periods, middle and high troposphere layers 500hPa and above have relatively strong frontogenesis. This is advantageous to the continued maintenance and strengthening of frontal zones. Because 850-700hPa low troposphere levels have frontal dissipation, this promotes further weakening of fronts until they completely disappear.

In Meiyu rainstorm periods, 300hPa and below is all frontogenesis. Moreover, middle layer frontogenesis is relatively strong. The terms playing the main roles are horizontal motion terms and nonadiabatic terms. Also, in middle zones, middle and high troposphere layers 400hPa and above have frontogenesis. The strength of frontogenesis 500hPa and below is very weak. Terms playing key roles are nonadiabatic terms and torsion terms. As a result, during Meiyu rainstorm periods in the Yangtze-Huai valley, frontal zones in middle and high troposphere layers on the north side of Meiyu cloud and rain belts are capable of continued maintenance because of frontogenesis. However, in low troposphere layers associated with air above cloud and rain belts, frontal structures are not clear. Frontogenesis strengths are also very small, causing the continued maintenance of this type of special structure associated with Meiyu fronts in rainstorm periods.

TABLE 3 AVERAGE FRONTOGENESIS FUNCTIONS ASSOCIATED WITH MEIYU INITIAL PERIODS AND MEIYU RAINSTORM PERIODS (Unit: °C/100km d)

(1)阶 段	(2) 梅雨初期								(3) 梅雨暴雨期							
p	F		F_H		F_V		F_∞		F		F_H		F_V		F_∞	
(hPa)	北区	中区	北区	中区	北区	中区	北区	中区	北区	中区	北区	中区	北区	中区	北区	中区
200	1.06	0.39	0.05	0.03	0.32	0.02	0.69	0.34	−0.49	0.17	0.03	0.07	0.15	−0.11	−0.67	0.21
300	0.48	−0.32	0.55	−0.86	1.69	−0.15	−1.76	0.69	0.76	1.36	0.67	1.81	0.72	0.17	−0.63	−0.62
400	1.37	0.06	0.77	−1.05	1.94	−0.02	−1.34	1.13	0.78	0.47	0.52	0.70	0.36	0.38	−0.10	−0.61
500	0.93	−0.09	0.74	−0.37	1.38	0.12	−1.19	0.16	0.48	0.01	0.28	−0.49	0.22	0.43	−0.02	0.07
700	−0.25	−0.34	0.24	−0.39	0.03	0.12	−0.52	−0.07	0.17	0.12	0.06	−0.26	0.14	0.01	−0.03	0.37
850	−0.07	−0.25	−0.19	−0.33	0.07	0.05	0.05	0.03	0.16	−0.11	−0.06	−0.14	0.18	0.04	0.04	−0.01

Key: (1) Level (2) Meiyu Initial Period (3) Meiyu Rainstorm Period (4) Northern Zone (5) Central Zone

Table 3 clearly shows that, whether it is during Meiyu initial periods or rainstorm periods, nonadiabatic heating--with regard to 500-300hPa middle and high troposphere layer frontal zones--has relatively strong frontogenesis functions. However, in the case of 850-700hPa low troposphere layer frontal zones or shear lines, there are relatively strong frontal dissipation effects. Because sensible heating effects are usually only limited to low troposphere layers, as a result, F_H here primarily reflects latent heating frontogenesis action. Moreover, in initial Meiyu periods, large scale latent condensation heat action (F_L) is relatively great. However, in rainstorm periods, latent troposphere condensation heat action (F_c), by contrast, is relatively strong (Table 4). This is primarily manifested in the Yangtze-Huai area during Meiyu initial periods as stabilized cloud and precipitation. However, in Meiyu rainstorm periods, by contrast, it is primarily manifested as the results of convective cloud and precipitation.

In Meiyu initial periods and Meiyu rainstorm periods, horizontal motion has relatively strong frontogenesis effects on middle and high layers. However, there are weak frontogenesis effects on low layer fronts or shear lines. This is closely related to Meiyu period horizontal circulation distribution characteristics. In Meiyu periods, troposphere layer frontal zones as well as rainstorm period low layer shear lines are always consistent with vortical shear lines and convergence. Moreover, this type of shear, in all cases, accompanies deformation fields associated with extension axes which are quasi east west directions. Included angles between the extension axes and horizontal surface fronts or shear lines are very small. As a result, this type of deformation field and divergence field have frontogenesis actions on fronts. Further analysis clearly shows that deformation field frontogenesis actions are somewhat greater than divergence fields.

In Meiyu initial periods, the bottoms of 700-300hPa frontal zones are strong cold sinking airflows. On the fronts, there are warm air flows slanting upward toward the north. In the vicinity of frontal zones, there exists clear thermodynamic direct circulation [12]. The horizontal distribution of this type of vertical movement causes middle and high layer frontal zone front dissipation. However, influences on low layer fronts are very small. Moreover, in Meiyu rainstorm periods, the areas behind 500-300hPa middle and high layer frontal zones are weak cold sinking air flows. The areas in front are strong ascending air flows rising almost vertically from low layers. This rising air flow--with low layer southwest air flows associated with the south side of rain and cloud belts as well as high layer northeast air flows--form a large, strong monsoon circulation ring [12]. This type of vertical circulation has front dissipation effects on middle and high layer frontal zones. However, on low layer fronts or shear lines, it has weak frontogenesis actions.

TABLE 4 FRONTOGENESIS FUNCTIONS CREATED BY CONDENSATION LATENT HEATING (Unit: °C/100km d)

(1) 阶段	(2) 梅雨初期						(3) 梅雨暴雨期					
p	F_H		F_L		F_C		F_H		F_L		F_C	
(hPa)	北区	中区	北区	中区	北区	中区	北区	中区	北区	中区	北区	中区
200	0.05	0.03	0.05	0.03	0	0	0.03	0.07	0.03	0.07	0	0
300	0.55	−0.86	0.24	−0.30	0.31	−0.56	0.67	1.81	0.21	0.67	0.46	1.14
400	0.77	−1.05	0.44	−0.45	0.33	−0.60	0.52	0.70	0.23	0.40	0.29	0.30
500	0.74	−0.37	0.15	0.09	0.59	−0.46	0.28	−0.49	−0.04	0.03	0.32	−0.52
700	0.24	−0.39	0.14	−0.21	0.10	−0.18	0.06	−0.26	0.02	−0.06	0.04	−0.20
850	−0.19	−0.33	0.03	−0.02	−0.26	−0.42	−0.06	−0.14	−0.11	0.02	0.04	−0.21

Key: (1) Level (2) Meiyu Initial Period (3) Meiyu Rainstorm Period (4) Northern Zone (5) Central Zone

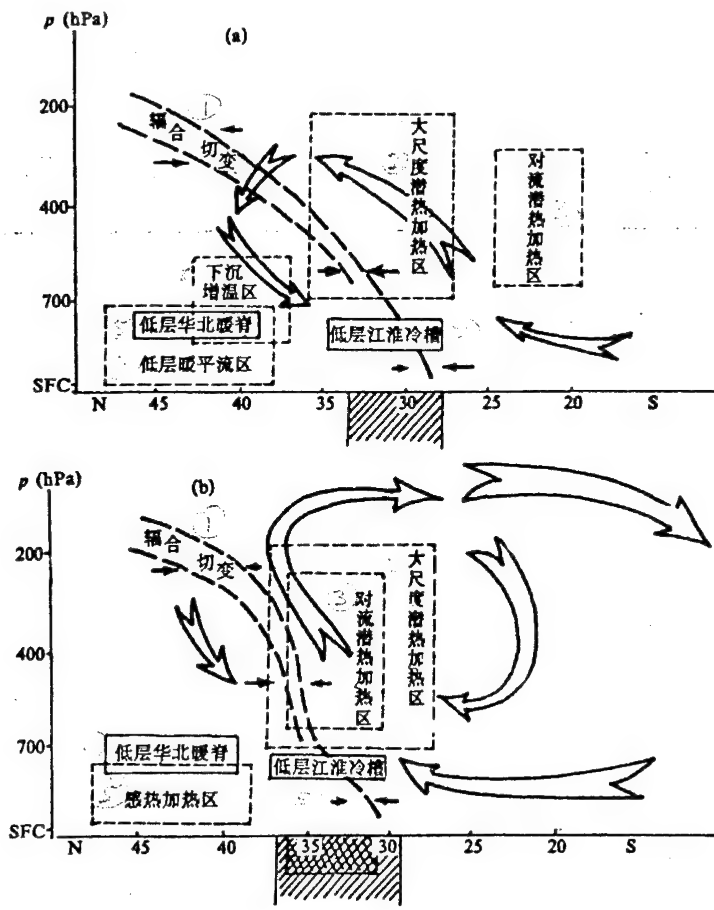

Fig.4 Meteorological Model for Meiyu Front Formation and Maintenance (a) Meiyu Initial Period

Key: (1) Convergence Shear (2) Large Scale Latent Heating Area (3) Convective Latent Heating Area (4) Sinking Warming Zone (5) Low Layer North China Warm Ridge (6) Low Layer Warm Advection Zone (7) Low Layer Yangtze-Huai Cold Trough (b) Meiyu Rainstorm Period (1) Convergence Shear (2) Large Scale Latent Heating Area (3) Convective Latent Heating Area (4) Low Layer North China Warm Ridge (5) Sensible Heating Zone (6) Low Layer Yangtze-Huai Cold Trough

In these, double thick broken lines represent frontal zones. Single thick broken lines represent vortical shear lines. Thin arrows represent frontal zone vicinity north south wind components. Thick double arrows represent radial vertical circulation. Dotted rectangle areas represent various types of heating and their ranges. Solid rectangle areas make clear the ranges of low layer temperature troughs and ridges. The bottom shaded areas represent properties and ranges of precipitation (the cross shaded areas are stable precipitation, the double shaded areas are convective precipitation).

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VI. CONCLUSIONS

This article analyzes the development processes associated with the 1981 Meiyu front from June 22-30. In conjunction with this, use is made of diagnosis associated with frontogenesis functions and temperature balance equations. It discusses the actions of factors influencing Meiyu front formation and maintenance.

Before the plum rains enter the middle and lower reaches of the Yangtze valley, clear large scale frontal areas exist in the troposphere. After the entry of the Meiyu, troposphere middle and upper layers still harbor large scale frontal zones. However, lower layer large scale frontal areas very quickly weaken and disappear.

Summarizing the analysis described above, it is possible to generalize out a meteorological model (Fig.4) for Meiyu front formation and maintenance.

In Meiyu initial periods (Fig.4a), northwest area strong sensible heating as well as North China area warm advection and sinking temperature increases are advantageous to lower layer warm ridge formation in the North China area. In the Yangtze-Huai area, cold troughs form, promoting lower layer frontal area weakening and disappearance. Latent heating plays a key role in maintaining middle and upper layer frontal zones. Distortion

fields created by horizontal motion and convergence fields also are advantageous to the maintenance of middle and upper layer frontal areas. Radial vertical circulation is a direct thermodynamic circulation around frontal zones. It acts to destroy middle and upper layer frontal areas.

During Meiyu rainstorm periods (Fig.4b), sensible heating distributions still are advantageous to the maintenance of North China warm ridges and Yangtze-Huai cold troughs. The key factor in maintaining middle and high layer frontal zones is still latent heating. However, the proportion of convective latent heat in latent heating has become the largest. The prime heating area has already moved north to the Yangtze-Huai river valley. Horizontal motion is still advantageous to middle and upper layer frontal zone maintenance. Radial vertical circulation primarily manifests itself as a strong, large monsoon circulation ring. It is not advantageous to the maintenance of middle and high layer frontal zones.

Because of this, the factors playing primary roles in the formation and maintenance of the special Meiyu front structure with upper layers having fronts and lower layers lacking fronts are sensible heating and latent heating.

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